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3 PROBLEMS AND TECHNIQUES OF LUNAR SURFACE MINING 6

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ABSTRACT

The utilization of minerals indigenous to the moon offers potential advantages to the space exploration program. Some laboratory experimental results are presented which pertain to the problems associated with the operation of a mine on the surface of the moon. Several surface mining techniques are discussed along with an estimate of the cost relative to the alternative of transporting the required products from the earth.

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RESEARCH PROJECTS LABORATORY
RESEARCH AND DEVELOPMENT OPERATIONS

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TECHNICAL MEMORANDUM X-53560

PROBLEMS AND TECHNIQUES OF LUNAR SURFACE MINING

SUMMARY

The feasibility of mining on the moon depends upon many factors, some of which cannot be well defined at this time. The two largest uncertainties are (a) the availability of quantities of desirable native materials which could be used for the production of fuel components and water, and (b) the magnitude of the lunar and planetary program which will determine the extent to which lunar resources will be used or needed.

Laboratory experiments and test programs have indicated that the physical characteristics of lunar surface materials may differ in several respects from those of terrestrial rocks and soils. The vacuum environment has been shown to have a pronounced effect upon porosity, bearing strength, adhesion, and the frictional characteristics of simulated lunar surface materials.

Studies have been made of several surface mining methods which could be adapted for use on the moon. The requirements for power, manpower, and ore production were considered in rejecting certain systems commonly used on earth. Crew safety, weight and delivery costs, simplicity of operation, and mine operations were other factors which further restricted the remaining systems to the ones presented.

These preliminary experiments, studies, and tests have indicated that surface mining on the moon may be advantageous if this nation's space program becomes large enough to require extensive lunar exploration or planetary exploration from a lunar base or colony.

INTRODUCTION

There are many potential advantages in the use of indigenous minerals in connection with the space exploration program over the alternative of transporting everything from the earth.

The safety and flexibility of lunar colonies and expeditions will be greatly enhanced by availability of lunar sources of supply. If return fuel and oxidizer are available on the moon, colonies will no longer be dependent solely upon rigid adherence to flight schedules from earth. In the event of a lunar plant or supply breakdown, fuel and oxygen can be supplied from the earth; if there are earth launch failures or delays, local supplies will insure that the colony is not endangered. If indigenous fuel materials are not available, a long-term supply from earth may be required for lunar storage.

The technological requirements for establishment of mining and processing facilities on the moon will not only tax man's ingenuity to the utmost but, just as is true of all the space programs, will produce an abundance of scientific data for the benefit of present technology and the advanced technologies required for later and longer-term expeditions to Mars and to other planets of the inner solar system.

The use of lunar resources, if they exist, will increase man's understanding of the geology and structure of the moon. The exploration for the mining of minerals should add significantly to the detailed knowledge to be gained from Apollo and post-Apollo scientific expeditions.

The effects of vacuum conditioning on granular rock materials are being investigated in the Research Projects Laboratory of MSFC. Some results of experiments are presented in this paper which concern the effects of grain packing factors, shape and size characteristics, and their surface roughness. Presented also are some results from certain atmospheric and vacuum experiments to determine the change in coefficient of friction between metals and rock material. This is related directly to the experiments on the adhesive properties and bearing strengths of such material in a vacuum environment. These experiments and studies are providing a better understanding of the mechanical properties of the material expected to be present on the surface of the moon. Results from these and other experiments are necessary for the proper design of lunar mining systems.

This report is an evaluation of the present problems and possible techniques to be encountered on the moon for surface mining of water deposits. An estimate of relative costs of several mining systems is made.

Finally, if it is found that indigenous lunar resources can compete economically with the same or similar materials transported from the earth, they will be utilized. If, however, this cannot be shown, the chances for the mining and use of these materials, even if deposits are present, are not probable and must await changes in supplies and economic position of earth materials.

FACTORS AFFECTING LUNAR SURFACE MINING

Environment

1. Vacuum. The most pronounced effect upon lunar surface operations will be the extremely low pressure and the physical effects associated with or caused by this near-vacuum atmosphere. Any surface mining operation will involve the suited astronaut working in this environment.

The maximum atmospheric density is known to be less than 10^{-6} that of the earth's atmosphere at sea level [1]. Estimates of the lunar surface pressure range from 1.3×10^{-10} N/m^2 to below 1.3×10^{-12} N/m^2 (1×10^{-12} - 1×10^{-14} Torr). J. de Wys [2] cites the work of Elsmore with the Crab Nebula occultation and states that the lunar atmospheric density is 10^{-13} that of the earth.

Some of the probable atmospheric constituents include water, carbon dioxide, and hydrogen. Carbon has been identified by Kosyrev from spectrograms of the crater Alphonsus [2].

As will be discussed later, the vacuum environment will probably impose severe constraints on the design of systems and equipment to be used in mining. The frictional and adhesive characteristics of lunar material will affect the power requirements of mining systems and ore transportation equipment. Lubrication of machinery, rock breakage and removal, and the stability of artificial slopes are all affected by the vacuum environment. The problem of lubricating bearing surfaces exposed to vacuum is well recognized. Slope stability is indicated by a material's angle of repose. The mine face or overburden slope should be more stable than the same slope angle on earth since the factors of vacuum adhesion, lunar gravity, and extreme particle roughness favor greater stability [3].

The astronaut must be protected, both from the hostile native environment and from the induced hazards associated with mining, such as machinery, blasting, rock falls, etc. Protection from mining hazards must be accomplished not only with the suit, but through proper design of equipment, techniques, and procedures to insure astronaut safety while he is performing the necessary related tasks. If the mining operation is large enough to require large mobile equipment, pressurized astronaut compartments will be required. The danger from rock debris is too great to allow the astronaut to be in an exposed location without protection while mining operations are in progress. If the lunar surface program is extensive enough to require a mining operation, even on a limited scale, subsurface shelters should be available to give protection during rock blasting or other high-hazard periods.

2. Thermal. The maximum and minimum observed infrared brightness temperatures of the lunar surface have been 400° K and 70° K while 220° K has been estimated at a depth below which diurnal solar heating is negligible [4]. Aside from the more obvious problems associated with the astronaut and his equipment, the thermal environment could impose some unusual mining problems. Assume the ore is covered by an overburned which has been stripped of its water to some depth by the interaction of vacuum, temperature fluctuations, solar wind, etc. The ore may be turned into overburden by exposure to these environmental conditions; this may require that the actual working face of the open pit be covered or otherwise protected. The depth to which ore could be turned into overburden would depend upon the extent to which the particular rock is susceptible to outgassing. Mining performed at night or in permanently shaded areas may reduce the gaseous emissions from the rock and allow an ore of higher water content to be extracted.

3. Solar Wind and Cosmic Debris. The lack of any appreciable atmosphere allows the alpha particles and protons of the solar wind to strike the lunar surface with full force. Infrared and ultraviolet radiation is more intense than here on earth. Whatever hard shelters are provided for vacuum and thermal protection should be adequate for the solar wind except during periods of high solar flare activity. No unique problems are expected with mining systems or operations because of the solar wind. Interruptions from time to time for personnel protection during flares may be an exception.

The high speed collision of meteoroids and micrometeoroids with the surface could be a real danger to the astronauts and to the surface-mounted equipment. The magnitude of the danger has not been fully determined primarily because the frequency, velocity, and mass of these impacting materials are not known. The particle sizes range upward from micron or submicron size to perhaps many meters, while their velocities could vary from 10 to 72 kilometers per second [5]. Estimates have been made [6] that the chances of a one-gram particle hitting an astronaut on the lunar surface are less than one in 3×10^{14}

earth days. A strong erosional process could result from the impact of much smaller particles. It has been estimated [7] that an area of 1 to 10^4 square centimeters of the moon is struck each second by a particle weighing more than 10^{-10} grams. The resulting erosion, either of native material or exposed equipment and structures, would be a product of this "lunar weather." This would give the appearance of a finely etched surface and would not be of major consequence except for unprotected optical surfaces or precision machined parts of machinery.

4. Lunar Gravity. Acceleration due to gravity on the moon is about 1.62 to 1.63 meters per second squared, or approximately 1/6 that of the earth. The earth's variable tidal attraction on the moon reduces the lunar gravity on the near side by 3×10^{-5} meters per second squared and increases it by the same amount on the far side. Lunar mining equipment would be designed for the mean gravity, as any anomalies should not be large enough to affect power requirements or load handling capabilities.

Lunar mining techniques will probably be modifications of conventional methods. The lower lunar gravity will allow increased drawbar pull and decreased rolling resistance of mobile equipment such as ore loaders, transporters, and other rolling machinery.

5. Vibration and Shock. Seismic activity would result from moonquakes and meteorite impacts or explosive shock caused by scientific experiments performed by the astronauts. Quakes and the shocks of impacts are potentially troublesome for mining operations. The stability of foundations, mine working faces, overburden slopes, and process equipment could be modified or destroyed. The magnitude of the forces involved must be determined from seismological data gathered from the moon.

Surface Structure and Strength

1. Texture. Photographic evidence from Surveyor I, the Ranger series spacecraft, and terrestrial observations is beginning to give a better understanding of the surface of the moon. Admittedly, Surveyor I data do not answer the question of the entire surface, but do give a view of one local area.

Earlier estimates of a rubble surface texture [3] are supported by the Surveyor pictures. The surface material is fragmented, porous, and partly smoothed by some process. The granular soil-like material shown on the photographs appears to range from fine grain to coarse. Some results of a preliminary analysis [8] are shown in Figure 1 as the cumulative frequency distribution of particles on the lunar surface. The material disturbed by the footpad of the spacecraft exhibits a more coarse texture than the undisturbed material. The more coarse disturbed material may be agglomerates of finer material. This indicates that the granular portions of the surface have a distinct amount of cohesion. It is, in some respects, qualitatively similar to a damp, fine-grain soil on earth.

The photographs show the surface to be littered with coarse blocks and fragments. The distribution of the larger blocks appears to be fairly random, but local concentrations can be seen on the flanks of recognizable craters. Most of these blocks are probably debris from within the crater and are thought to consist of relatively strong rock [8].

The implication from the Surveyor I data is that relatively solid rock lies beneath the surface rubble. This is the potential ore from which water could be extracted to support extensive lunar exploration. If the depth of rubble is not too great, surface stripping would not be as difficult as opening an underground mine and could be done with fewer men and less equipment.

2. <u>Strength.</u> There are indications [8] that this surface has a static bearing capacity on the order of 4×10^5 dynes per square centimeter or 5 pounds per square inch. A man who weighs about 80 kilograms (180 pounds) would exert a pressure, while standing, of about 2.1×10^5 dynes per square centimeter or 3 pounds per square inch here on earth. If this strength increases with depth, which is reasonable to assume, stable support foundations can be constructed. Considering the small depth to which the footpads penetrated the surface material, vehicle sinkage and rolling resistance should not be a significant problem.

However, other areas could have quite different surface characteristics and engineering properties. If some erosional and transportation process has been operating on the moon, there could be areas of local deposition of material which are supported by an openly dendritic structure. If such a soil profile exists, its strength could be so low as to preclude normal surface operations. This soil structure need not be composed of dust or micron-sized particles to have this characteristic if the vacuum adhesion or cohesive tendency is strong enough to bond individual pieces as they are deposited. If such areas do exist, it is expected that they would be local in nature and not abundant.

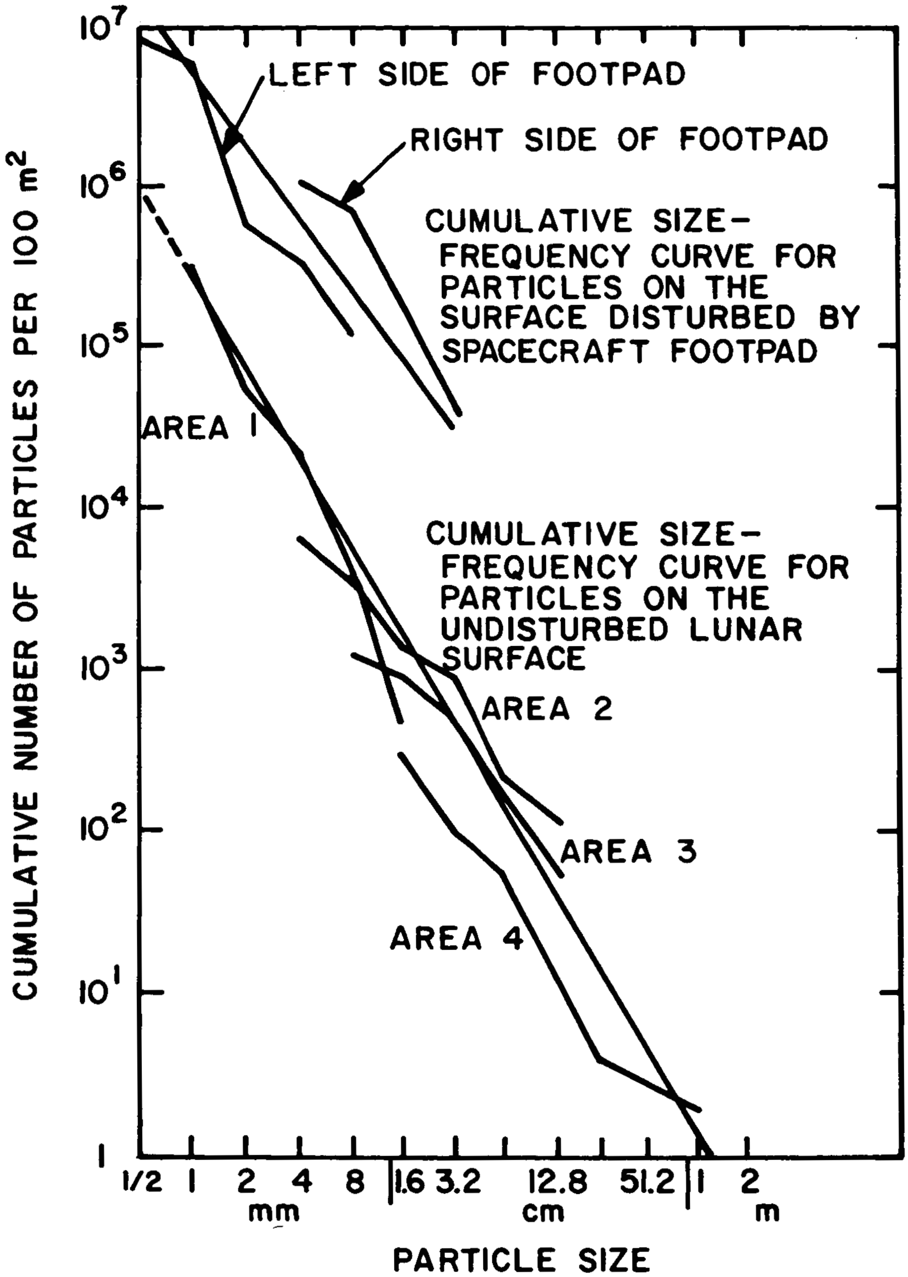

FIGURE 1. CUMULATIVE FREQUENCY DISTRIBUTION OF PARTICLES ON THE LUNAR SURFACE [8]

Material Behavior in Vacuum

The behavior of material in a lunar environment is of interest to designers of lunar equipment and planners of lunar missions. This is of particular interest to mining engineers because of the necessity to handle and transport mass quantities of surface and subsurface material. There are many methods of mining which could be used on the lunar surface. Some of these are discussed in detail later in this paper. The method of mining selected for use on the lunar surface will be determined after a large number of variables have been evaluated. Some of these will be equipment weight, power requirements, astronaut participation, lunar surface and subsurface composition and the effect of the lunar environment on the properties of these materials.

There is a large effort being put forth by a number of scientists to evaluate the effect of a lunar environment on the physical and mechanical properties of simulated lunar materials. The program is complicated because of the large number of variables to be considered and tests often necessary to establish reliability in the observed results. Ultra high vacuum is probably the most influencing parameter of the lunar environment on the mechanical characteristics of rock material. Consequently this is usually the first variable to be studied in the laboratory and appears to be of major importance in lunar mining problems.

Vacuum technology today will allow experiments to be made at a pressure of 10^{-9} Newtons per square meter (10^{-11} torr) if caution is used and small amounts of test apparatus and sample are admitted to the vacuum chamber. Much of the data available today in the literature was taken at pressures of 10^{-4} to 10^{-6} Newtons per square meter (10^{-6} to 10^{-8} torr) and can be used to give indications as to the effect of vacuum on the mechanical properties of simulated lunar materials. However, caution should be exercised in extrapolating this to the lunar vacuum.

Of particular interest to those concerned with lunar surface mining is the effect of the vacuum on the coefficient of friction between engineering materials and the lunar surface material. Also of importance is the possibility of lunar surface material adhering to engineering materials with which it comes in contact when disturbed by operations on the lunar surface. These two problems are being studied and a detailed discussion follows.

1. Friction. The effect of a vacuum environment on the coefficient of friction of two metal surfaces has been studied in detail. However, despite this widespread interest in metals, very little study has been directed toward the coefficient of friction of metals on simulated lunar materials.

Some studies have been made to determine friction and wear of various combinations of aluminum, steel, basalt, and rhyolite slabs at ambient pressure, in an argon atmosphere, and at a vacuum level of 10^{-7} Newtons per square meter (10^{-9} torr) [9]. This study was oriented toward the wear portion of the program. The coefficient of friction was studied as a function of speed, load, and pressure. Figure 2 [9] shows how the coefficient of friction varied with load, generally decreasing as the load increased, for aluminum on aluminum and aluminum on basalt. The coefficient of friction was larger in vacuum than in atmosphere in each test regardless of the load applied.

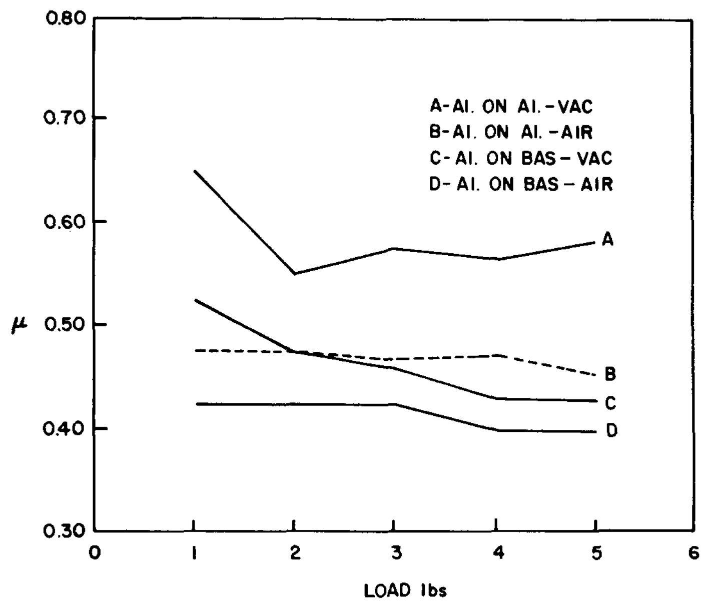

FIGURE 2. COEFFICIENT OF FRICTION VERSUS LOAD [9]

An experimental program is currently in progress to study the effect of vacuum on the coefficient of friction of metals on granular nonmetallic materials. The metallic materials are aluminum 7075, steel AISI-1020, and 321 stainless steel. The nonmetallic materials are quartz and basalt in the size ranges 37 to 44 microns and 250 to 500 microns in diameter. Selected tests are also performed on a 50 percent mixture (by volume) of these sizes.

Initially, tests were performed with both aluminum and steel on the granular size classifications above. These tests were performed at atmospheric pressure and in an oil diffusion pumped vacuum system at 10^{-4} to 10^{-5} Newtons per square meter (10^{-6} to 10^{-7} torr). The vacuum system contained a liquid nitrogen-cooled baffle between the pump and chamber to inhibit the migration of oil into the chamber.

The coefficient of friction is higher in vacuum than in atmosphere for all tests completed during this phase of the program. However, there are many variables which influence the measured values. Some of these cause an increase while others cause a decrease in the measured coefficient of friction.

Tests were made in vacuum at a temperature of 160°C. The coefficient of friction was lower than that in identical tests at ambient temperature but higher than in atmospheric tests at ambient temperature. This would be expected because as the sample is heated, gas molecules are driven out, resulting in a higher net pressure at the surface of the sample than would be measured at some other location inside the chamber. Also, the measured value for the coefficient of friction is a function of the surface roughness of the metallic sample. In some tests the same metallic sample was used in pre-vacuum, vacuum and post-vacuum. In all cases, the post-vacuum results were higher than pre-vacuum, with the vacuum results higher than either.

The values obtained in this phase of the program are given in Table I [10].

TABLE I. COEFFICIENT OF FRICTION FOR METALLIC AND NONMETALLIC MATERIALS

	Quartz			Basalt		
	37 to 44μ	250 to 500μ	Mixture	37 to 44μ	250 to 500μ	Mixture
Steel AISI-1020						
ATM	0.21	0.09	-	0.28	0.15	-
VAC	0.29	0.16	-	0.62	0.29	-
Aluminum 7075						
ATM	0.23	0.18	0.25	0.31	0.21	0.22
VAC	0.34	0.58	0.39	0.41	0.24	0.26

In an effort to evaluate the results listed in Table I and to determine the single effect of vacuum on the coefficient of friction, a series of tests was performed using aluminum 7075 on quartz 250 to 500 microns in diameter. The oil diffusion pump was replaced by an ion pump to prevent the possibility of coating the surfaces with oil.

In this phase the coefficient of friction obtained in atmosphere was 0.15 compared to 0.18 in the previous phase. The value obtained in a vacuum of 10^{-5} Newtons per square meter (10^{-7} torr) was 0.30 compared to 0.58 in the previous phase. This value of 0.30 is little more than half the previous value of 0.58, and it appears that the results in Table I are high for the vacuum because the metal sample was used in atmospheric tests prior to the vacuum tests. However, the values of Table I can be taken as upper limits for the vacuum tests.

Another series of tests was performed using 321 stainless steel on the coarse quartz at a vacuum of 10^{-5} Newtons per square meter (10^{-7} torr). The coefficient of friction was determined to be 0.15 at ambient temperature and decreased to 0.14 with an increase in temperature to 150°C.

In tests using metallic hemispheres in contact with basalt and quartzite solids, the coefficient of friction increases from atmosphere to a moderate vacuum of 10^{-4} to 10^{-6} Newtons per square meter (10^{-6} to 10^{-8} torr) [11]. The coefficient of friction on quartz increased from 0.19 to 0.29 for steel AISI-1020, and from 0.16 to 0.25 for aluminum 7075. Likewise, for basalt the coefficient of friction increased from 0.14 to 0.28 for steel AISI-1020 and from 0.21 to 0.28 for aluminum.

Experimental results have shown that the increase in moderate vacuum of the coefficient of friction between engineering materials and nonmetallic materials is not severe. Unfortunately, these results cannot be extrapolated with any confidence to a lunar vacuum. However, one can be certain that as the vacuum increases, the coefficient of friction will increase.

2. Adhesion. There is general agreement that a layer of dust is present on the lunar surface. However, the thickness of this layer has not been established; estimates range from kilometers [12] to a few millimeters [13]. Likewise, there are two primary hypotheses of the origin of the lunar craters - impact and volcanic. Either origin would result in the deposit of some fine granular material on the lunar surface and, in fact, both mechanisms have probably been active on the moon.

The very high quality photographs of the moon taken by Rangers VII, VIII, and IX and more recently by Surveyor I (Fig. 3) leave little doubt that at least some areas of the moon are covered by granular material.

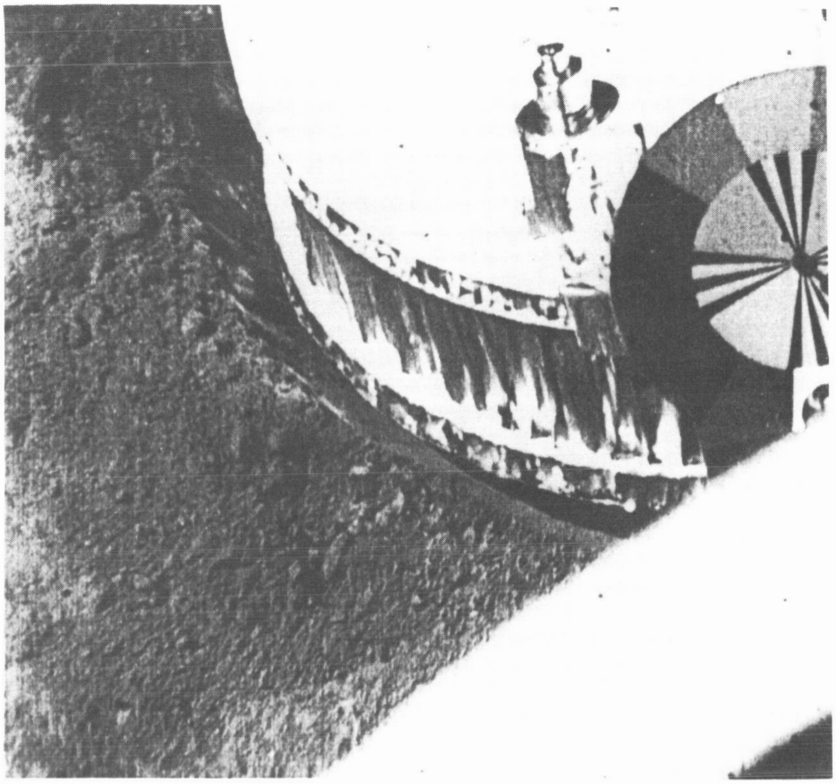

FIGURE 3. SURVEYOR I SPACECRAFT FOOTPAD

The presence of a fine layer of dust on the surface of the moon could be an obstacle to mining operations, affecting man, vehicles, and machinery. The degree to which it will be an obstacle depends primarily upon its mechanical properties. Recent experiments indicate that the mechanical properties of a granular material in a lunar vacuum will be dominated by cold welding of the material.

Single crystal minerals have been contacted in a vacuum of 10^{-8} Newtons per square meter (10^{-10} torr) [14]. Some of the tests were made with crystals cleaved in air, while others were made with crystals cleaved in vacuum. The crystals cleaved in air exhibited adhesive forces up to about 0.4 gram while the crystals cleaved in vacuum have had forces of a magnitude larger. Fine powdered rock including chondrite, tektite, obsidian, basalt, andesite, dunite, and pyroxenite was sieved in a vacuum and adhered to the sample holder and wires leading to the apparatus [15]. Samples of fine powdered basalt and slightly larger aluminum powder were shown to adhere at a vacuum of 10^{-8} Newtons per square meter (10^{-10} torr); however, the basalt tests were not always repeatable [16].

Experiments have been conducted using basalt, pumice, crushed glass, and glass spheres to determine the adhesive forces in an oil-free vacuum as high as 10^{-9} Newtons per square meter (10^{-11} torr). The test apparatus consisted of a 304 stainless steel drum, a variable speed motor, and a magnetic rotary seal. The drum was 25 centimeters long and 15 centimeters in diameter. The drum contained 4 slats 1.3 centimeters high extending the length of the drum. One end of the drum is closed by a plate containing 4 ports of fine mesh wire to allow gas to escape. The other end is closed by a glass window to allow viewing of the sample while the experiment is in progress.

The results will be discussed briefly here and are given in detail by Fields [17]. Basalt (180 grams) in size ranges 10 to 20, 20 to 37, and 37 to 62 microns in diameter was tumbled at 1 RPM until 100 percent adhesion occurred. With each sample, adhesion began immediately with rotation of the drum and 100 percent adhesion occurred in 15 minutes for the two smaller sizes, and in a slightly longer time for the larger size. Figure 4 shows the drum with basalt immediately after bringing the sample to atmospheric pressure with dry nitrogen.

The initial pumice tests indicated very weak adhesive forces with about 20 percent of 180 grams adhering after rotating 24 hours. However, later tests have indicated that this is a gas emission problem. If the pumice is exposed to vacuum of approximately 2 weeks instead of 3 days, the adhesive forces are considerably stronger.

Samples of identical composition but different shape characteristics were studied to determine the effect of surface configuration on the adhesive forces. Crushed glass and glass spheres were each tested in the size range 20 to 37 microns. Approximately 99 percent of the crushed glass adhered after 30 minutes with no further increase after 24 hours. Approximately 30 percent of the glass spheres adhered after 24 hours.

Mineral Deposits

Just as fundamental as lunar surface and environmental problems are those of the kind, grade, extent, structure, and location of the deposits that may contain water or other useful minerals. At this point we have no direct evidence of the presence of mineral deposits at all. The presence of water or any other mineral deposit must be inferred at the present time and inferences must, in turn, depend upon assumptions regarding lunar origin, thermal history, chemical composition, and extent of near-surface chemical differentiation. No attempt will be made to explore here the many possibilities that have been suggested and reported.

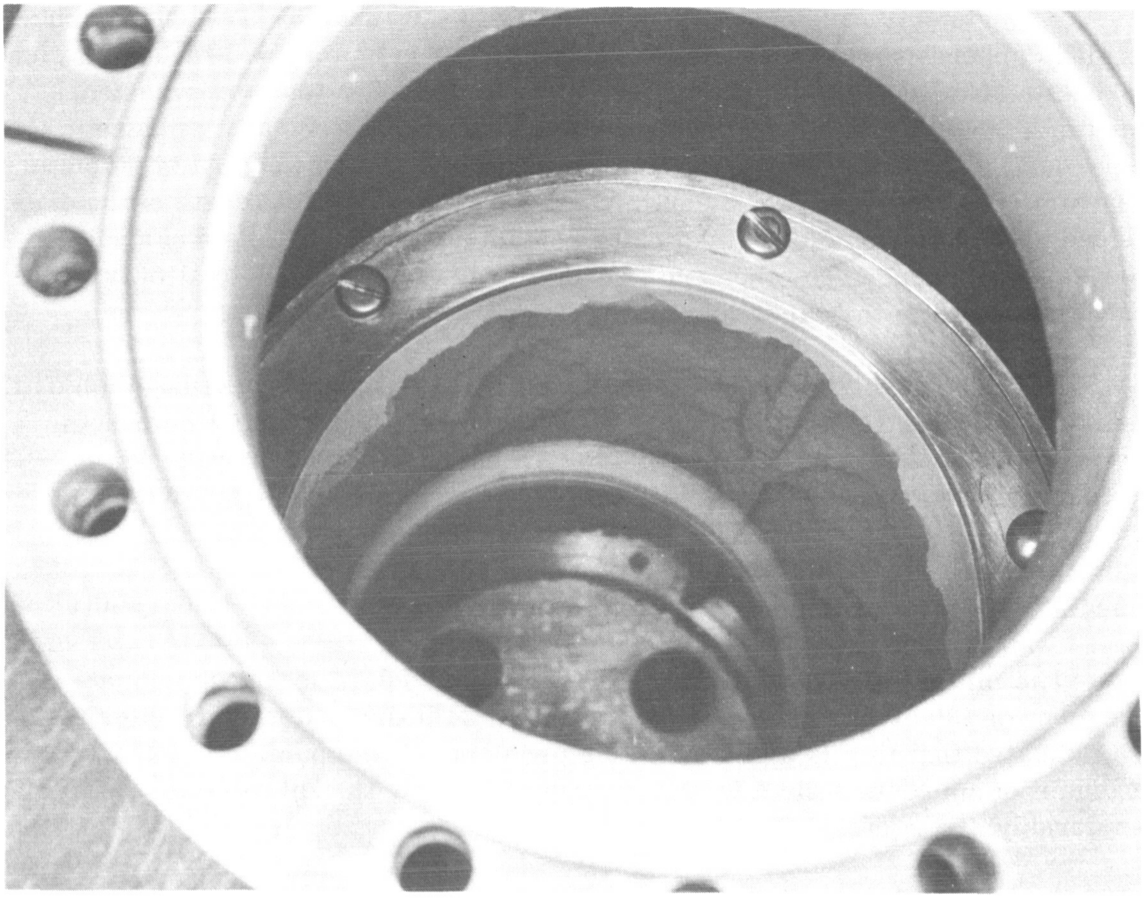

FIGURE 4. BASALT ADHERED TO STAINLESS STEEL DRUM IMMEDIATELY AFTER RELEASE TO ATMOSPHERE PRESSURE

At the present time, when considering mining problems and techniques, it will be necessary to cover the entire range of possible chemical differentiation of the lunar crust. In a previous report [6] twelve deposit models were examined. They ranged from strictly impact origin to both intrusive and extrusive volcanic models. Ten of them were taken from the work of Salisbury [18, 19] and of Westhusing and Crowe [20]. Nine of the twelve models are associated with the lunar maria. Of the nine, four imply that the maria consist of bedded tuff layers, three that they are filled with successive lava flows, and two could be interpreted as a filling from one thick lava outpouring. One lunar upland model consists of a single rubble blanket over granodiorite, a second, of interbedded, lenticular rubble layers over granodiorite, and a third, a rubble layer alone, with imbedded serpentine boulders.

If lunar mineral deposits occur in the form of local mineral enrichments, as do earth deposits, a program for their discovery, evaluation, and exploitation will be necessary. If they can be associated early with surface features (maria edges, crater bottoms, crater rims, lunar domes) or with visible or hidden structural features (fracture systems, fluid vents, etc.) or if they are found to occur in groups or geographic districts, as on earth, the problem of discovery and evaluation will be greatly simplified. Unless concentration does occur to some extent, drilling or other exploration to evaluate the deposit will be useless and mining will become merely the random removal of country rock.

Water occurring in free form should be more economical to mine and process than chemically combined water. If free water occupies pores, shear zones or small fractures in hard or tough rock, mining it will be almost as difficult as for hydrous minerals in similar rock. Permafrost zones in tuff and similar free water deposits should be much less difficult to mine.

In free water deposits, ice may be accompanied by other frozen volatiles. Some of these may introduce problems of corrosion of mining equipment. For example, if titanium alloys are used in the construction of lightweight equipment and chlorine were present with the ice, severe damage to the titanium parts could occur. Although chlorine attacks titanium very slowly when wet, dry chlorine gas (less than 0.5 percent water) "may react at room temperature," according to one source [21], while another reference [22] states "rapid attack, ignited and burned" (less than 0.1 percent water at 30°C). In any mixture of chlorine and water, the evaporating chlorine would likely be dry because the boiling point of chlorine at 1 atmospheric pressure is -34.6°C, and the vapor pressure of water at that temperature is only a little more than 0.1 millimeter of mercury.

Some other corrosive substances are bromine, ammonia and steam, calcium chloride, chlorine trifluoride, fluoboric acid, fluorine, flurosilic acid, hydrochloric acid (concentrated), hydrofluoric acid, mercury (371°C), phosphoric acid (boiling, concentrated), potassium hydroxide, sodium bifluoride and sulfuric acid (less than room temperature) [21]. Most of these substances attack titanium only at moderate rates. In general, titanium and its alloys may be attacked if the lunar chemistry proves to be strongly reducing. "Titanium provides excellent resistance to general and localized attack under most oxidizing, neutral and inhibited reducing conditions. It also remains passive under mildly reducing condition, although it may be attacked by strongly reducing or complexing media" [21].

Other surface mining problems may be related to the lunar day and mineral deposit location. It will be assumed that all early lunar landings and activities, except possibly lunar exploration, will be limited to the landing belt, 10 degrees on either side of the lunar equator. Here, a surface mine for approximately half the lunar day would be subjected to the direct rays of the sun with results noted above, if the ore is free water. Ores consisting of hydrous minerals should not be affected.

For surface mining operations, however, there would be certain advantages to night operation, independent of ore composition. Some of the advantages of night-time operations will be: (a) uniformly low temperature conditions, (b) uniform lighting from the earth, (c) absence of solar wind, (d) possible absence or reduction of rarified ionized gases of the thin lunar atmosphere, (e) possible absence or reduction of a postulated surface electric charge, (f) no cooling needed for space suits and/or machine cabs or structures, and (g) better heat dissipation from bearings, motors, etc.

Possible disadvantages of night operation are: (a) the necessity to provide artificial lighting, at least part of the time, (b) the high heating load for space suits, cabs, and structures, (objectionable only if primary power is solar and battery storage is required for night operation), and (c) the increase in freezing of working fluids, if any are used.

Equipment Problems

Many problems will be encountered in the selection and design of lunar mining equipment. The first automobile resembled a buggy, so it is quite likely that the first lunar mining equipment will be earth models, modified for the lunar environment and mining conditions. This is one assumption on which the present work on mining systems is based. After some lunar mining experience, undoubtedly original and different equipment designs will be developed. If lunar mining is preceeded by a considerable period of lunar exploration, there will be opportunity for new designs to be applied to transportation vehicles and methods and to drilling techniques. Any underground shelter construction activities, prior to mining, would also give some experience in problems of fragmentation, digging, loading, and limited-scale excavation. These activities may, however, resemble underground mining more than surface methods.

Problems considered to date may be classified as (a) power supply; (b) mode of traction for moving equipment; (c) equipment control methods;

(d) materials for equipment construction and (e) secondary or service materials, such as for ballast or counterweights, maintenance facilities, roads, bins, crusher foundations, control systems and power distribution systems.

1. Power Supply. Although no fundamental studies of types of equipment power have been made, it is assumed that alternating current electrical power will be used. Most small surface mining equipment on earth has gasoline or diesel engines, while larger shovels and draglines depend upon diesel-electric or electric power. No great trouble is anticipated in substituting electric motors for diesel engines in small equipment. One manufacturer of bulldozers and loaders writes: "Successful conversions from diesel engines to electric motors have been made in some underground mines in this country and abroad."[1] Evidently, this conversion was applied to bulldozers or loaders manufactured for diesel engines and substitution should be much easier at the time of manufacture and assembly. Substitution of electric motors for diesel or gasoline engines should result in a net weight reduction.

Electrical energy may be generated centrally and distributed by lines to stationary installations or through trailing cables to moving equipment. If fuel cells or other compact generation equipment is used, cell and motors may be individual for each piece of equipment. Detailed consideration of these problems is beyond the scope of this paper.

2. Mode of Traction for Moving Equipment. Present small equipment moves on treads or on wheels, usually rubber-tired. Larger shovels and draglines are crawlers or walkers. Mitchum [23] concluded that tracked vehicles are less efficient than wheeled ones. They are heavier and less reliable and their only superiority, which is slight, is in soft, dry granular material. It is assumed that tracked vehicles will be used for mining equipment, because (1) Surveyor I photographs indicate the probable presence of such material; (2) wheels must be rather large to cross cracks easily negotiated by equal-sized crawler vehicles; and (3) the practicability of lunar use of pneumatic tires is questionable.

3. Equipment Control Methods. Mining equipment may conceivably be controlled by: (1) an operator in a space suit, much as in operations on earth, a method probably practical only for lunar night work; (2) an operator in an enclosed, earth-environment cab mounted on each piece of equipment, whether

[1]Mr. W. O. Mooney, Caterpillar Tractor Co., personal communication.

bulldozer, loader, shovel, or dragline; (3) remote, automatic controls from an earth-environment shelter especially erected at the mine or from the crew living shelter which may or may not be located at the mine; or (4) remote, automatic control from the earth. The last two control methods probably will require continuous television viewing.

At least one mining system using central control at the mine and a number of others using either of the first two methods will be considered. The necessity to study the first two in detail has been eliminated by limiting our study to lunar night work. Neglected also are real "remote" control systems.

It is readily acknowledged that systems (1) and (2) will use more lunar-based labor than will the others and that this large cost item may constitute its greatest handicap.

4. Materials for Equipment Construction. Excavating equipment is constructed almost entirely of steel and cast iron. Since transportation of equipment from earth to moon probably will be the greatest single charge against the utilization of indigeneous lunar resources [24], some way must be found to reduce weight without impairing the usefulness of the equipment.

Large draglines, and perhaps some shovels, make some use of aluminum, especially in booms. One manufacturer writes of a particular model: "We might also add that the 120-foot boom consists of 45-foot steel butt, 38-foot aluminum insert and 37-foot aluminum top."[1] Thus, 75 feet of the boom length was made of aluminum. It weighed 8780 pounds, which is probably far less than equivalent steel parts would weigh. Cabs and other parts normally subjected to comparatively low stresses may also utilize aluminum.

Parts of machines carrying maximum stresses often cannot be made of aluminum or magnesium. Many of these, however, may be replaced by titanium or titanium alloys. Beryllium alloys are also a possibility. One manufacturer [25] reports yield strengths of 9.99×10^8 Newtons per square meter (145,000 pounds per square inch) for Ti-6Al-4V alloy sheet and plate, and 10.07×10^8 to 11.31×10^8 Newtons per square meter (146,000 to 164,000 pounds per square inch) for extruded shapes. This compares with about 6.89×10^8 Newtons per square meter (100,000 pounds per square inch) for heat-treated constructional steels [26]. Titanium may not be so desirable with regard to some other properties, but it is said to have superior strength-to-weight ratios, excellent

[1]Mr. J. T. Kaminski, Manitowoc Engineering Co., personal communication.

elevated temperature performance, good corrosion resistance and unusual erosion resistance [27]. Nothing was found in manufacturers' data on properties at low temperatures like those of the lunar night, but the mean thermal coefficient of expansion (32° to 212° F) is 4.9×10^{-6}° F (8.82×10^{-6}° K) for Ti-6Al-4V alloy [21] as compared to about 7×10^{-6}° F (12.60×10^{-6}° K) for 0.2C steel; thus, titanium should not be as strongly stressed by rapid temperature changes as is steel.

Densities are approximately 1.74 grams per cubic centimeter for magnesium; 2.70 grams per cubic centimeter for aluminum; 4.5 grams per cubic centimeter for titanium; 7.85 grams per cubic centimeter for steel; and 4.43 grams per cubic centimeter for the alloy Ti-6Al-4V.

One manufacturer[1] lists weights of five bulldozers, three crawler loaders, and one wheeled loader with the weights of steel used in their construction. The bulldozers averaged 88 percent steel, the loaders 89.4 percent, and the wheel loader, 91.3 percent. All steel can hardly be replaced by titanium or aluminum. Titanium, for example, probably does not have the wear resistance of the steel used for bulldozer blade cutting edges, although one manufacturer says "..titanium has been successfully flame-plated with tungsten by the Linde process,"[2] a treatment that should make it much more abrasion-resistant. The weights of earth-designed equipment will be estimated if Ti-6Al-4V alloy is substituted for much of the steel and if electric motors are substituted for diesels. The latter substitution may not bring any real weight reduction if heat-dissipation radiators have to be added to electric motors. These probably would be made largely of aluminum, and it is doubtful if the heat-dissipation systems for electric motors would weigh as much as the brass cooling radiators of gasoline and diesel motors. Also, if fuel cells or batteries must be added to the electric motors, there may even be some increase in weight over diesel engines. Trailing cables will add weight for this method of electric power distribution.

It must be remembered that lifting, but not necessarily scraping or loading of soil or broken rock on the lunar surface, should require only one-sixth the power required for the same volume lifted on the earth. Thus, the power required for equivalent volumetric performance of equipment may well be much less on the moon than on earth. If lunar materials are also of lower density than earth materials, even less power will be required.

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[1]Mr. L. J. Hill, Allis-Chalmers Manufacturing Co.

[2]Mr. G. H. Hille, Reactive Metals, Inc.

5. Secondary or Service Material. The final category of secondary or service materials is not discussed in this paper except as follows: There is every reason to believe that there should be on or near the lunar surface a considerable accumulation of meteoritic nickel-iron. Whether it occurs in discrete, large or small masses, or as condensed vapor from the heat of impact, dispersed throughout the lunar soil is not known. If it can be collected, it should be ideal for ballast or counterweight in construction equipment needing such material. A given volume of it, of equivalent density, should be six times as effective for this use as the same volume would be on earth. Some large equipment manufacturers do not ship ballast, but at the time of equipment erection it is provided locally from scrap iron or concrete. If counterweights must be monolitic, small meteorite iron masses in concrete would be ideal. Green [28] has suggested cast basalt as a possible concrete substitute.

The second comment is prompted by the necessity for an ore chute or bin as the minimum auxiliary facility required at a mine. If mining and haulage can be combined in one operation, such as with a scraper-loader, the bin or chute could be placed at the processing plant and ore hauled there directly. If ore is loaded into vehicles (trucks) by a front-end loader, shovel, or dragline, or if it is merely stockpiled at the mine and loaded and shipped later, no chute or bin may be required. As will be seen later, however, any scraper mining system or any automatic control system will require some kind of chutes or bins. If the ore is to be crushed at the mine, at least a chute and a foundation will be required. As will be shown in illustrations following, it is proposed that metal posts be used for such structures. In earth soil, these could be placed by a piledriver; this would be possible also in the lunar soil shown in Surveyor I photographs provided it is deep enough and there are no large boulders, meteorites, iron masses, etc., to prevent driving. If these conditions or solid rock exist, posts could still be placed in drilled holes.

TECHNIQUES

Mining Systems

After learning something specific about the occurrence of lunar minerals and certainly after some mining experience, surface mining systems may be developed which are entirely unlike any now used on earth. Until that time, however, little can be done except to apply variations of earth methods which seem suitable to current concepts regarding lunar mineral deposits.

High unit costs and limited water demand for fuel or other purposes will require that early lunar water mining be simple, on a small scale and at a cost equal to or lower than that of transporting water from the earth. If accessible supplies of ice can be found in caverns, lava tunnels, etc., near the lunar equator, no water will be mined, in the usual sense, but it will merely be "harvested." If, however, water is found only under the lunar surface, at depths too great to be affected by the lunar diurnal temperature cycle, mining logically can be contemplated. As the demand for water, oxygen and hydrogen for lunar colonies and for fuels increases, it is reasonable to expect the size and sophistication of mining operations also to increase.

Virtually nothing has been published on "conventional" mining methods applicable to lunar conditions. Heyward [29] has discussed the general problem, pointing out the separate functions involved in mining and processing indigenous lunar resources: rock-breaking, loading, size reduction, transportation, processing and purification, conversion, and storage. Some work has appeared on indirect methods of mining, similar to the Frasch process and to solution mining [30,31], tunneling methods [32] and a general review of published work on lunar mining [33].

The work reported here deals with the more conventional surface, strip or open cast mining systems. Indirect systems and mining by drilling are also conducted from the surface but involve the removal of very limited quantities of overburden.

Systems for surface mining of water may be classified as follows:

1. Scraper methods

    a. Stationary engine-operated scraper.

    b. Scraper drawn by a tractor or other vehicle.

    c. Scraping ore and overburden by bulldozer.

    d. Removing overburden and ore by scraper-loader.

2. Methods involving scraping of all or part of the overburden and digging of ore or ore and part of overburden.

    a. Overburden removed wholly or partly by scraper, bulldozer or scraper-loader and ore dug and loaded by front-end loader or hoe.

b. Overburden, wholly or partly removed by scraping and ore or ore and harder overburden, dug by power shovel.

c. Same methods as above except for ore removal by dragline.

d. Overburden and ore both dug and removed by shovel or dragline.

3. Methods involving fragmentation of ore and of part or all of overburden prior to digging and removal.

   a. Overburden removed wholly or partly by scraping and ore and part or all of overburden fragmented for removal by shovel or dragline.

   b. All ore and all overburden fragmented before removal by shovel or dragline.

   c. All ore and overburden fragmented (Digging and loading may be done with front-end loader or hoe.)

It will be noted that the methods have been roughly arranged in order of increasing hardness or toughness of overburden and ore. Surveyor I photos proved that at least part of the lunar surface is covered, to an undetermined depth, by material which probably can be scraped and removed. Under the impact hypothesis, there must be a considerable thickness of rubble both on the maria and terrae that may be scrapable if it contains no or few large boulders or has not become firmly cemented in some way. If the maria are younger than the terrae, the rubble blanket there probably is thinner. If the maria are volcanic tuff flows or falls, the material may be scrapable to considerable depth unless extensively intruded by lava.

The classification of mining methods is also arranged according to increasing size of mining equipment. Small shovels and draglines will weigh more than bulldozers or loaders, and cable-drawn scrapers are even lighter.

Of the methods listed, only 1.a. can be made mechanically automatic or operated by one man from a single on-site location. The other methods will require an operator in a space suit or in a pressurized cab on each machine or electronic controls installed in each machine and operated from a central control tower or booth. High resolution television viewing may be required in remote control systems if overburden and ore are difficult to distinguish.

In the classification, it is assumed that hardness or toughness of overburden and ore may increase with depth and that ore will be harder than at least a part of the overburden. This assumption appears reasonable for hydrous mineral ores, and probably, for lean free water ores.

Definition of Model Water Deposit

Six hypothetical ore deposits have been defined for use in comparing suitability and first order relative costs of various mining systems. Only one basic model will be used in this paper. It will be used as two deposits with differing depths of overburden.

1. Deposit

a. The ore is a uniform permafrost zone, 3 meters (9.84 feet) thick, in a friable volcanic tuff (Fig. 5).

b. The zone lies at a uniform depth of 10 meters (32.8 feet) below a generally level mare surface (similar to Surveyor I terrain). Overburden is a dry "semiwelded" tuff with an average bulk density of 1.25 grams per cubic centimeter (78 pounds per cubic foot).

c. The deposit location is within 10 degrees of the lunar equator.

d. The ore contains 2 per cent free water and has a bulk density, in place, of 1.20 grams per cubic centimeter (75 pounds per cubic foot) [34].

2. Mining Schedule. One schedule suggests a lunar oxygen demand of 4546 kilograms per month (10,000 pounds per month) or 54,552 kilograms per year (120,000 pounds per year) by 1976 and double this quantity in 1982 [24]. The 1928 quantity will be used for estimates. It is equivalent to 122,728 kilograms (270,000 pounds) of water per year. On this basis, ore averaging 2 percent water, by weight, must be mined and processed at the rate of 6,136,367 kilograms (13,500,000 pounds) per year, if extraction is 100 percent efficient. It shall be arbitrarily assumed that 6,818,200 kilograms (15,000,000 pounds or 7500 tons) is the basic annual quantity to be mined from either of the above deposits.

a. Mining will be assumed to be limited to one 8-hour shift per 24 hours and to lunar night only. The lunar night is equal to 13.66 earth days

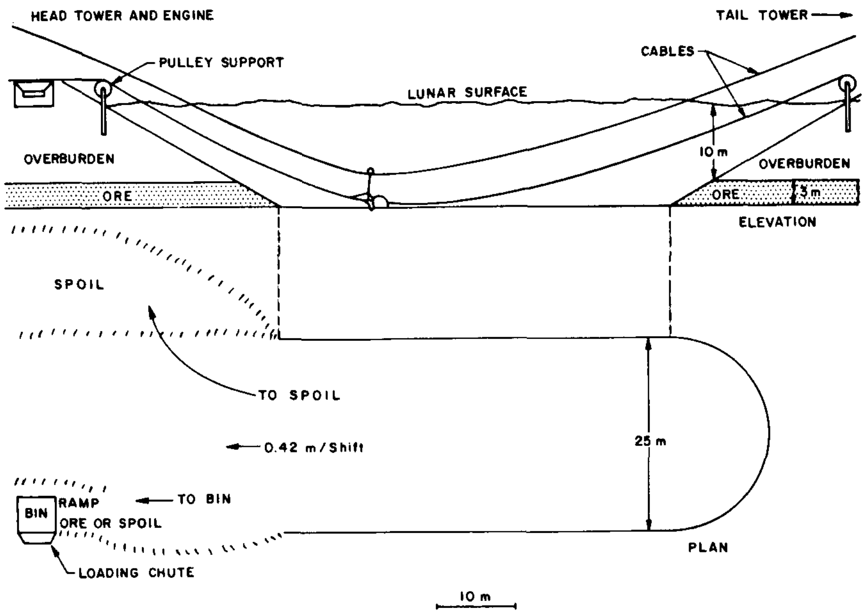

FIGURE 5. SCHEMATIC DIAGRAM OF A PROPOSED ROPE-AND-SCRAPER MINING SYSTEM

and there are 13.37 lunar nights per earth year. This gives 182.63 shifts per year. For simplification of calculations, 180 shifts per year will be used. If mining is also done during the lunar day, mining may be expanded to 360 shifts.

b. For 180 shifts, the mining rate will be 37,879 kilograms (83,333 pounds) ore per shift.

c. In the assumed deposit, the ore volume that must be mined is 31.566 cubic meters per shift. The thickness (and volume) of overburden to be moved is 3 1/3 times that of ore so that the volume of ore and overburden to be moved per shift totals 136.8 cubic meters.

d. Alternate calculations will be made for the same ore thickness but for an overburden depth of 30 m or 10 times that of the ore thickness. This deposit will require removal of 347.2 cubic meters of material per 8-hour shift.

e. If a pit width of 25 meters (82 feet) is arbitrarily assumed, the distance that the pit must be advanced, each shift, to remove 31.566 cubic meters of ore, 3 meters high and 25 meters wide, will be only 0.42 meter. In a year this will be only 75.6 meters or 3 times the pit width. With a low rate of pit lengthening, haulage distances will increase only slowly. In a relatively narrow pit, stationary scraper systems will require infrequent shifting of end towers or pulleys.

Mining Capacities of Some Equipment

1. Figure 5 shows a rope-and-scraper system for mining the ore zone at either 10- or 30-meter depth. This system is similar to larger scale tower excavators on the earth. Figure 6 is taken from a publication advertising this kind of system [35]. Such a system should be operable by one man from a central booth.

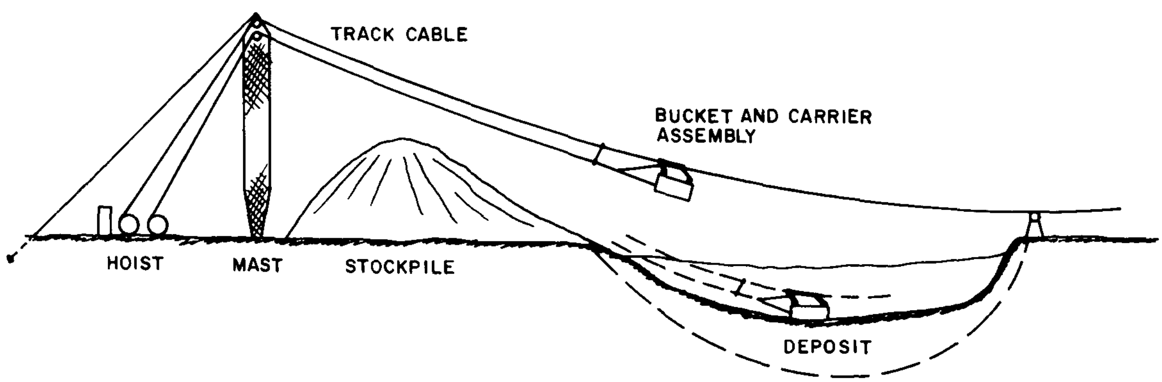

FIGURE 6. SCHEMATIC DIAGRAM, SLACKLINE CABLEWAY EXCAVATOR [35]

The capacity of a scraper system will be determined by its rate of transport rather than by its rate of digging. The transport rate is a function of scraper or bucket capacity and of the cycle frequency. Cycle frequency may vary slightly for overburden and ore. Figure 5 shows overburden deposited on a spoil pile with the ore dragged to a chute. The ore-to-chute distance is almost constant and that for waste disposal gradually increases.

One manufacturer [36] advertises scrapers from 66 to 213 centimeters (26 to 84 inches) wide. If height is 61 centimeters (24 inches) and material piles in front of the scraper at a 45 degree angle, the two sizes can carry 0.12 and 0.40 cubic meters (0.16 and 0.52 cubic yards) per trip. The larger scraper is only half the capacity of the smallest bucket used on a small-duty dragline manufactured by one company.

Figure 5 indicates that at the stage of mining shown (Another bin must be installed to the left of the one shown and the ramp extended to it.), the distance of ore transport is about 30 meters. If the other bin is installed

50 meters farther left, the distance of drag will be about 80 meters. If one assumes an average drag distance for ore of 50 meters, and for spoil a longer one of 70 meters, the average is about 60 meters. The lowest speed listed for a small tractor was 1.2 miles per hour or 1.932 kilometers per hour. Adopting this speed for dragging, recognizing that the return drag to the pit for both ore and spoil is unproductive, and assuming that dumping time will require half the time required for a one-way trip, the equivalent drag distance per productive load is 150 meters. This gives 12.88 loads per hour or 103 loads per shift. With the 66-centimeter (26-inch) scraper, this is 12.36 cubic meters (16.21 cubic yards) with the 213-centimeter (84-inch) scraper, it is 41.20 cubic meters (53.56 cubic yards) per shift. Thus, neither of the scrapers has sufficient capacity to secure the required output of 136.8 cubic meters of material per shift.

A scraper 213 centimeter (84 inches) wide and 76 centimeter (30 inches) high has a capacity of 0.62 cubic meters (0.81 cubic yards) per trip or 63.8 cubic meters (83.4 cubic yards) per shift. Even two of these in tandem will not mine the 10-meter overburden deposit at a sufficiently rapid rate.

If a 1.34-cubic meters (1.75-cubic yards) dragline bucket can be used in the place of scrapers and still attain the same dragging speeds, 138.0 cubic meters per shift can be moved and the smaller deposit can be mined at the required rate.

A 3.37-cubic meters (4.41-cubic yards) bucket would be needed to mine the deeper overburden deposit at the same dragging speeds.

The mechanics of operating a rope-and-scraper system with a forward end or engine end and a tail pulley indicate that a rigid-position set-up will make it almost impossible to run a wide pit. The scraper will be difficult to direct to all parts of an essentially rectangular pit without frequent moves or without use of side ropes and pulleys to guide the scraper, first to the spoil pile and then to the ore bin. A round pit, with the head end in the center, would require frequent moving of only the tail pulley. A narrow pit would require frequent moves forward. Undoubtedly, this method cannot be quite as productive as has been calculated because some allowance must be made for the time required for moves.

2. An alternative and much more flexible scraping system would be a scraper drawn by a tractor. This method probably will require an operator in a space suit or in a tractor cab. It should also prove the ideal method, if it becomes necessary to mine a large number of small, scattered deposits rather than a large one.

The pit layout could be similar to that shown in Figure 5, but with much more latitude as to location of spoil piles and loading chutes.

The limiting factor in material transportation capacity for this mining method probably will be very close to that of the previous one. It is possible that the average length of haul could be shortened and the haulage speed might be increased by using a larger tractor than one with a 1.93 kilometers per hour (1.2 miles per hour) speed.

3. A very similar mining method is one in which ore and overburden are scraped by a bulldozer to loading chute or spoil pile.

A very wide variety of bulldozers are available. The limiting capacity factor again will not be digging rate, but transporting rate. Using the assumption of material piled against the blade at a 45-degree angle, Table II shows the capacities of the smaller dozers on which information was collected. It also shows the capacities of each at 1.93 kilometers per hour (1.2 miles per hour) and at the fastest low gear speed of any of the bulldozers 2.74 kilometers per hour (1.7 miles per hour). The minimum number of bulldozers required to handle both 10 and 30 meters of overburden, plus 3 meters of ore, at the low speed, are also shown.

Considerably larger bulldozers are made than those listed in Table II, but they are also much heavier. A mining installation using this system will need a minimum of two machines in order to keep production going in case maintenance is needed on the principal mining machine.

4. A pit layout similar to that of Figure 5 may be preserved if overburden and ore are dug, transported, and dumped by front-end loaders. Table III gives data for 16 small front-end loaders. The bucket capacity (level rather than heaped, where both are given) is the average of the range given by the manufacturer. It is evident that for equivalent capacity, rubber tired models are considerably lighter than crawlers. For consistency, however, only the crawler models will be used for cost comparisons. If wheeled vehicles prove satisfactory for haulage on the lunar surface, there exist additional possibilities for weight reductions. Even if rubber tires prove impractical, large, light metal wheels should prove sufficiently strong and much lighter than crawlers.

Table III illustrates that the small loaders move materials faster than bulldozers—in some cases, with the same tractors. No one crawler-loader, however, was sufficiently large to handle the 10-meter overburden deposit.

TABLE II. WEIGHTS, DIGGING, AND SCRAPING CAPACITIES OF SMALL BULLDOZERS (CRAWLER TYPE)

Machine No.	Power	Blade Length	Blade Height	Transport. Capacity		Capacity Per Shift(1)		Capacity Per Shift(2)		No. Dozers To Handle		Weight(5)	
				M^3	Yd^3	M^3	Yd^3	M^3	Yd^3	10m	30m	Kg	Lb
1	(3)	80"	24"	0.378	0.494	38.9	50.9	55.1	72.1	4	9	2,828	6,228
2	(3)	80"	24"	0.378	0.494	38.9	50.9	55.1	72.1	4	9	3,301	7,272
3	(3)	83.9"	28"	0.539	0.705	55.5	72.6	78.7	102.9	3	7	3,953	8,707
4	(4)	110"	28"	0.706	0.924	72.8	95.2	103.1	134.9	2	5	4,998	11,009
5	(4)	121-5/8"	27-3/4"	0.740	0.968	76.2	99.7	108.1	141.3	2	5	5,148	11,340
6	(4)	96"	33.2"	0.867	1.134	89.3	116.8	126.7	165.6	2	4	5,147	11,336
7	(4)	124-3/4"	34"	1.182	1.546	121.8	159.2	172.6	225.7	2	3	7,054	15,538

(1) 103 trips per 8 hours at 1.2 mph

(2) 146 trips per 8 hours at 1.7 mph

(3) Gasoline or diesel.

(4) Diesel.

(5) With substitution of Ti-6Al-4V alloy and Al for part of steel.

TABLE III. WEIGHTS, DIGGING, AND TRANSPORTATION CAPACITIES OF SMALL FRONT-END LOADERS

Machine No.	Power	Bucket Capacity(7)		Capacity Per Shift(1)		Capacity Per Shift(2)		No Loaders To Handle		Weight(6)		Traction
		M^3	Yd^3	M^3	Yd^3	M^3	Yd^3	10m	30m	Kg	Lb	
1	(3)	0.99	1.30	102.4	133.9	145.1	189.8	2	4	1,683	3,708	R
2	(3)	1.11	1.45	114.2	149.4	161.9	211.7	2	3	2,128	4,687	R
3	(4)	1.06	1.38	108.6	142.1	154.1	201.5	2	4	3,154	6,948	R
4	(3)	0.62	0.81	63.8	83.4	90.5	118.3	3	6	3,432	7,560	C
5	(3)	1.25	1.63	128.4	167.9	182.0	238.0	2	3	3,465	7,632	R
6	(3)	1.25	1.63	128.4	167.9	182.0	238.0	2	3	3,661	8,064	R
7	(3)	0.76	1.00	78.8	103.0	111.6	146.0	2	5	4,086	9,000	C
8	(5)	0.86	1.13	89.0	116.4	126.2	165.0	2	4	4,846	10,674	C
9	(5)	1.53	2.00	157.5	206.0	223.3	292.0	1	3	5,459	12,024	R
10	(5)	1.72	2.25	177.2	231.8	251.2	328.5	1	2	5,532	12,186	R
11	(3)	1.77	2.31	181.9	237.9	257.9	337.3	1	2	5,680	12,510	R
12	(5)	1.00	1.31	103.1	134.9	146.3	191.3	2	4	5,720	12,600	C
13	(3)	1.77	2.31	181.9	237.9	257.9	337.3	1	2	6,194	13,644	R
14	(5)	1.53	2.00	157.5	206.0	223.3	892.0	1	2	6,397	14,090	R
15	(5)	1.15	1.50	118.1	154.5	167.4	219.0	2	3	6,789	14,954	C
16	(5)	1.15	1.50	118.1	154.5	167.4	219.0	2	3	7,028	15,480	C

(1) 103 trips/8hr. at 1.2 mph
(2) 146 trips/8hr. at 1.7 mph
(3) Gasoline or diesel.
(4) Gasoline only.
(5) Diesel only.
(6) With substitution of Ti-6Al-4V alloy and Al for part of steel.
(7) Average of range given by manufacturer.
(R) Rubber tired.
(C) Crawler.

5. Both the deposits can also be mined by shovels and draglines. Because the "reach" of each of the machines is limited and their mobility restricted, some kind of ore haulage will be needed. To place the ore mined by shovels in bins located as they were in the previous examples would, however, require only very short hauls. If it is assumed that ore, regardless of the system of mining, must be hauled one kilometer to the preparation plant, bins are unnecessary for any of the nonscraping methods, including shovels and draglines because the ore may simply be piled on the surface for later loading and hauling. In this case, systems using front-end loaders, shovels and draglines will not need to be charged with any greater haulage costs than will scraper methods, unless elaborate preparation of the area for ore piling is needed.

Draglines have greater capability for mining below machine level than do shovels although the latter can make "box" or first cuts, after which all mining can be at machine level and above in a deposit like that shown in Figure 5. The shovel will, however, generally work in the pit bottom while the dragline can work from the surface. With 10-meter thick overburden, all the machines shown in Table IV should be able to mine all material in one bench. For 30-meter overburden depth, removal in not less than two benches will be necessary.

Loads that can be picked up by draglines decrease as boom length becomes greater. On the moon, both boom weight and equivalent volume load are less than on earth so that boom lengths and consequently, mining depths may be correspondingly greater. The same conclusions with regard to boom lengths and mining heights should be true of shovels, but to a lesser degree.

The capacities shown in Table IV indicate that both the shallow and the deep deposit can easily be handled by even the smallest draglines and shovels. The larger machines have considerable excess capacities under the assumptions made—in many cases, more than double. The No. 1 shovel and the No. 1 and No. 8 draglines are not grossly oversized for the deposits chosen.

Fragmentation-Blasting on the Moon

The determination of the blasting pattern, the quantity of explosives, and the detonation sequence for effective rock breakage are the main problems that must be solved for efficient blasting of any rock material. The trial and improvement method of developing satisfactory procedures is expensive but feasible in earth operations; however, it would be essentially impossible for lunar operations. In addition, there is no way of determining if a method so developed is the most efficient or economical.

TABLE IV. CAPACITIES, WEIGHTS, AND OTHER DATA ON FIVE SMALL SHOVELS AND NINE DRAGLINES

Machine No.	Power	Bucket[1] Capacity		Max. Height[2]		Oper. Radius[3]		Capacity[4] Per Shift		Weight[5]	
		M^3	Yd^3	M	Ft	M	Ft	M^3	Yd^3	Kg	Lb
						SHOVELS					
1	(7)	1.44	1.88	9.0	29.5	9.0	29.5	552	902	31,160	68,550
2	(7)	2.29	3.00	11.8	38.8	12.1	39.8	881	1440	46,770	102,900
3	(7)	2.68	3.5	26.8	88.0	11.5	37.6	1028	1680	57,360	126,200
4	(7)	1.91	2.5	7.6	24.8	9.5	31.0	734	1200	49,600	109,400
5	(8)	1.91	2.5	9.1	30.0	11.3	32.0	734	1200	57,000	125,600
						DRAGLINES					
1	(7)	1.44	1.88	29.0	95.0	13.7	45.0	732	902	34,680	76,300
2	(7)	2.48	3.25	35.4	116.0	16.8	55.0	954	1560	42,100	92,200
3	(7)	2.68	3.5	35.7	117.0	16.8	55.0	1028	1680	48,260	106,400
4	(7)	1.72	2.25	-	-	-	-	864	1080	50,670	111,700
5	(8)	1.82	2.38	-	-	-	-	698	1142	52,300	115,300
6	(7)	2.01	2.63	-	-	-	-	772	1262	54,100	119,200
7	(8)	2.20	2.88	-	-	-	-	846	1382	58,900	129,900
8	(7)	1.15	1.50	18.3	.60	10.7	35.0[6]	441	720	26,200	57,250
9	(7)	2.68	3.50[6]	21.3	.70	12.2	40.0[6]	1028	1680	58,540	128,800

(1) Average of range given by manufacturer;
(2) Not given in literature of one manufacturer. For draglines, some data probably are for max. boom length, other for optimum.
(3) For shovels only. Max. digging depth for longest boom, for draglines.
(4) For cycle time of 60 sec.
(5) Adjusted for 10% non-steel, 10% steel, 65% Ti-6Al-4V alloy and 15% Al or a factor of 0.62x earth wt.
(6) Not given but estimated from other models of similar weight.
(7) Diesel.
(8) Electric.

NOTE: Some machine weights apparently include counterweights. One manufacturer's weights include "maximum ballast."

The present state of knowledge concerning the mathematical calculation of the explosive charge has been developed to a fairly high degree, but much remains to be done. Most formulas to date have been based on a particular usage, with no general formula available.

This section of the report will attempt to trace the development of current formulas and modify them for lunar use.

1. General Case. The force generated by an explosive must break as well as move the rock; it has to overcome the resistance against breakage and against gravitational forces. Belidor recognized this dual resistance of rock as early as 1725 [37,38]. He stated that one part of the charge was proportional to the strength of the rock and the other proportional to the volume excavated. He proposed the formula

$$Q = a V^2 + b V^3 , \tag{1}$$

where Q = explosive charge;
V = burden (least line of resistance);
a = constant based on rock strength; and
b = constant based on gravitational force.

Because early interest centered about military applications (i.e., the formation of craters), Belidor's work was quickly forgotten and replaced by the classical cube-rule (proposed earlier by Vauban) which is based on the law of conformity. Simply stated, the explosive charge is proportional to the volume of the crater produced. The cube-rule is expressed as

$$Q = k v^3, \tag{2}$$

where k = constant based on rock type.

Based on the results of extensive research since World War II, Langefors and Kilhstrom [39] have developed the following general formula which is an extension of Belidor's formula to include a "through" or "swell" component:

$$Q = k_2 V^2 + k_3 V^3 + k_4 V^4 \tag{3}$$

where k_2, k_3, and k_4 are constants dependent on rock type. They additionally reported that for ordinary bed rock,

$$Q = 0.01 V^2 + 0.40 V^3 + 0.004 V^4 \tag{4}$$

where Q is in kilograms and V is in meters.

A close look at equation (3) shows the following facts of interest:

(1) For small blasts ($V < 1$ meter) the strength of the rock is of most importance.

(2) For relatively large high explosive blasts ($1 < V < 10$ meters) the volume of material to be excavated is of greatest importance.

(3) For larger high explosive or nuclear blasts ($V > 10$ meters) the amount of throw is of considerable importance.

Kochanowsky's work [37], based on the results of numerous test blasts, had also suggested the variability of rock resistance as related to the size of the blast. He made the following postulations:

(1) The larger the piece of rock to be blasted, the greater the points of weakness and, therefore, the smaller the specific strength.

(2) The larger the burden, the further the material must be thrown for effective excavation.

These considerations explain the past failures resulting from the use of the cube-rule to predict the results of large blasts from the analysis of small test blasts.

The equation developed by Langefors and Kilhstrom is the general prediction formula for crater blasts, and as such gives reliable results when applied with the appropriate constants for each rock type. Assuming ordinary lunar rock to be similar in strength and mass to earth bed rock, the prediction equation for crater blasts can be applied to determine if high explosives could be used economically for blasting lunar rock.

Based on the preceding assumption, the first term of equation (4) would remain the same, but the second and third terms would have to be modified to account for the change in gravity. Since lunar gravity is approximately one-sixth that of earth gravity, the second term would be $0.07\ V^3$ and the third $0.0007\ V^4$. This indicates a greater proportion of the explosive will be required to break the rock in lunar operation than on earth. Rewriting the equation, we have

$$Q_L = 0.01\ V^2 + 0.07 V^3 + 0.0007 V^4, \tag{5}$$

where Q_L is lunar explosive charge in kilograms.

A more meaningful comparison can be made if the equations are converted to calculate the specific charge (kilogram per cubic meter). This can be accomplished by dividing through by V^3 to obtain:

$$q = \frac{0.01}{V} + 0.4 + 0.004 V \tag{4a}$$

$$q_1 = \frac{0.01}{V} + 0.07 + 0.0007 V, \tag{5a}$$

where q is specific charge on earth (kilogram per cubic meter)

q_1 is specific charge on moon (kilogram per cubic meter)

Calculation of the specific charge required for burdens ranging from 0.01 to 100 meters have been calculated and shown in Table V for comparison. Also included is a ratio of the lunar specific charge to the earth specific charge (n).

TABLE V. SPECIFIC CHARGE CALCULATIONS FOR EFFECTIVE FRAGMENTATION ON THE EARTH AND MOON

Burden (meters)	Specific Charge (kg/m^3) Earth (q)	Moon (q_1)	Ratio q_1/q (n)
0.01	1.400	1.070	0.764
0.10	0.500	0.170	0.340
1.00	0.414	0.081	0.196
10.00	0.441	0.078	0.177
100.00	0.800	0.140	0.175

The calculations shown in Table V indicate that the most efficient blasts are those conducted with burdens between 1 and 10 meters on both the earth and moon. Also it will be noted that as the burden increases, the ratio n decreases and approaches one-sixth.

It is a well-known fact that in earth operations, the specific charge for bench blasts varies from approximately 0.2 kilogram per cubic meter for soft rock to 0.6 kilogram per cubic meter for hard rock. Assuming the same relationship for bench blasting on the earth and moon as for crater blasting, it can be predicted that the specific charge for lunar bench blasting will vary from approximately 0.04 kilogram per cubic meter for soft material to 0.12 kilogram per cubic meter for hard material.

Assuming that most of the "ores" to be mined initially will have a mass of approximately 2,454 kilograms per cubic meter, it will require between 16.5 grams per metric ton (0.033 pounds per ton) mass to 49 grams per metric ton (0.098 pounds per ton) mass of explosive to effectively fragment and excavate the ore.

Because of a lack of a definite cost figure for sending supplies to the moon, Table VI has been developed to give an idea of the quantity of explosives in kilograms required to produce 1 kilogram of water for various grades of "ore."

TABLE VI. ESTIMATED AMOUNT OF EXPLOSIVES REQUIRED TO PRODUCE WATER ON THE MOON

Grade of Ore (percent)	Explosives required (kg per kg of water) soft "ore"	hard "ore"
1	0.0017	0.0049
5	0.0003	0.0010
10	0.0002	0.0005
100 (ice)	0.00002	-----

From Table VI it can be concluded that the relative cost of explosives necessary to produce water on the moon is small compared to the cost of shipping water to the moon assuming a constant cost per pound for supplies.

If a chemical explosive or blasting "agent" can be developed that will be stable and safe to use in the lunar environment, it should be feasible to use explosives for fragmentation and excavation.

In later work, the conclusions approximated in Tables V and VI will be applied to specific explosives and to their use in selected model deposits.

RELATIVE FIRST ORDER MINING COSTS

Many items enter into the cost of a mining operation. Capital costs for buildings, installations and equipment are the principal ones before production begins. Labor, transportation, maintenance, processing, etc., constitute the principal post-production costs. Of the mining methods discussed in this paper, the cost of buildings and other installations should be approximately independent of mining method. A possible exception is the stationary engine scraper system in which mobile equipment is simpler but installations (towers, control booth, etc.) are more elaborate than for the other methods. The cost of both installations and equipment will consist of the original cost and cost of transportation to the mining site on the moon. The latter cost is likely to so far overshadow initial cost that the original cost probably can be ignored. Total cost of transporting each machine will arbitrarily be charged to only 180 shifts (one year) in determining comparative costs per shift.

After production starts, labor is likely to dwarf all the other post-production costs listed. For example, the cost of maintenance is likely to include 90 percent or more maintenance labor. Selection of crew members will include one extra man and one maintenance man in addition to one operator for each machine.

In this first order cost study we plan to ignore installation cost differences and to base estimates solely upon cost of equipment transportation from earth at $5,000 per pound of payload [24] and cost of lunar-based labor at $100,000 per man hour [40]. The cost of labor for an 8-hour shift thus will be $800,000 per man.

It is recognized that factors like power consumption, differences in the life of machines, manpower rotation schedules, cost of processing ore, converting to hydrogen and oxygen, storage of products and possible profits from by-products (iron, diamonds, useful fluids other than water, structural materials, sulphur, etc.) will all enter into the total economic balance between utilization of indigeneous water and the importation of water and fuels from the earth, but this study is restricted to the two major costs of surface mining alone. The results of the application of four mining systems and of fourteen equipment models are shown in Table VII.

TABLE VII. COMPARATIVE COSTS, FIVE MINING SYSTEMS, AND FOURTEEN EQUIPMENT MODELS

Mining System		Equipment Item No.	Manpower requirement, ovb.		Manpower, Cost per shift, $		Equipment requirement		Equipment, Cost per shift, $		Total Costs per Shift		Cost Ratios	
			10m	30m	10m	30m	10m	30m	10m	30m	10m	30m	10m	30m
2 c	Scraping ore with bulldozer (page 21)	2	6	11	4.8×10^6	8.8×10^6	4	9	0.80×10^6	1.82×10^6	5,600,000	10,620,000	1.513	2.662
		3	5	9	4.0	7.2	3	7	0.69	1.60	4,690,000	8,800,000	1.268	2.205
		5	4	7	3.2	5.6	2	5	0.63	1.58	3,830,000	7,180,000	1.035	1.799
		7	4	5	3.2	4.0	2	3	0.86	1.30	4,060,000	5,300,000	1.097	1.328
2 a	Dig & Scrape, front-end loaders (page 21)	4	5	8	4.0×10^6	6.4×10^6	3	6	0.63×10^6	1.26×10^6	4,630,000	7,660,000	1.251	1.920
		7	4	7	3.2	5.6	2	5	0.50	1.25	3,700,000	6,850,000	1.000	1.717
		12	4	6	3.2	4.8	2	4	0.70	1.40	3,900,000	6,200,000	1.054	1.554
		15	4	5	3.2	4.0	2	3	0.83	1.25	4,030,000	5,250,000	1.089	1.316
2 d	Power Shovels (page 22)	1	3	3	2.4×10^6	2.4×10^6	1	1	1.90×10^6	1.90×10^6	4,300,000	4,300,000	1.162	1.078
		2	3	3	2.4	2.4	1	1	2.86	2.86	5,260,000	5,260,000	1.422	1.318
		4	3	3	2.4	2.4	1	1	3.00	3.53	5,400,000	5,930,000	1.459	1.486
2 d	Draglines (page 22)	1	3	3	2.4×10^6	2.4×10^6	1	1	2.12×10^6	2.12×10^6	4,520,000	4,520,000	1.222	1.133
		4	3	3	2.4	2.4	1	1	3.10	3.60	5,500,000	6,000,000	1.486	1.504
		8	3	3	2.4	2.4	1	1	1.59	1.59	3,990,000	3,990,000	1.078	1.000

Conclusions

If the assumptions upon which the figures in Table VII were based have reasonable validity, and the selection of equipment models is representative, a number of conclusions can be drawn regarding the relative cost ratios and the influence of manpower and equipment costs on them, for both the thin and the thick overburden deposit.

(1) The compatibility of the capacity of a machine or several machines to the ore requirements and deposit depths is very important. If a machine or group of machines is oversized, it will not be economic to ship; if undersized, manpower costs go up sharply.

(2) The smaller machines (bulldozers and front-end loaders) are generally more economical than the grossly oversized shovels and draglines for the shallower deposit. An exception is the light No. 8 dragline which was exceeded in economy only by two front-end loaders and one bulldozer.

(3) Of the fourteen machines selected, eight were within 20 percent of being as economical as the leading one for the smallest deposit. The eight include all front-end loaders, except one, and half the bulldozers. In view of the broad assumptions made and the random choice of machine capacities, it probably is fair to say that all eight of these machines are roughly equivalent. Only one bulldozer, a shovel and a dragline are more than 50 percent more costly than the most economical machine. The bulldozer is grossly undersized and so many of them are required that manpower costs are high and the other two machines are so grossly oversized that the cost of shipping to the moon is excessive.

(4) Two small draglines and the smallest shovel appear among the eight most favorable machines with ranks of fourth, seventh, and eighth. Their rankings are attained in spite of their being considerably oversized.

(5) Fitting the fourteen machines to the deeper deposit brings some interesting changes in order of economy. All the shovels and draglines, although still with excess capacity, move into the top eight in rank. This is true, not only of the small ones but also of the next size category (less than 3 cubic yards).

(6) The leading front-end loader for the small deposit dropped to tenth place when applied to the large deposit. The larger manpower needs and the

larger number of machines places the small machines at a disadvantage. Provision for remote control operation would lower the manpower costs but not the need for multiple machines.

(7) The largest front-end loader ranks only fourth and the largest bulldozer only sixth when applied to the deeper deposit.

(8) Only two additional machines come within 20 percent of the economy of the leading small dragline and seven are more than 50 percent greater than the costs of the smallest dragline. Both the most economical front-end loader and bulldozer are more than 30 percent as costly. The cost spread is much wider in these rankings than for the shallower deposit because most of the equipment on the list is simply too small for the deeper deposit.

As a general conclusion, it appears obvious that for maximum mining economy, the ore deposit must be carefully explored and evaluated; the product demand must be accurately known and mining equipment of the proper type and capacity to fit the deposit must be selected. This conclusion, which is not surprising, holds true on the earth as well.

It is evident that, even for the first-order study, the present one is not complete. Insufficient data have been obtained on scraper systems, on scraper-loaders and on all systems involving ground fragmentation prior to digging and loading. More work needs to be done also on power and power distribution systems, on drilling, and on transportation of ore from mine to mill.

REFERENCES

1. NASA 1965 Summer Conference on Lunar Exploration and Science, at Falmouth, Massachusetts, July 19-31, 1961. NASA SP-88, National Aeronautics and Space Administration. Washington, D. C., 1965, p. 363.

2. De Wys, J.: Surveyor Project Lunar Scientific Model, by L. D. Jaffe, Section 3.6. Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, April 1, 1966, p. 1.

3. Bensko, J., Cortez, J. L., Fields, S. A., and Weathers, H. M.: Lunar Logistics System, MTP-M-63-1, "Lunar Surface Conditions," Vol. VIII. G. C. Marshall Space Flight Center, Huntsville, Alabama, March 15, 1963.

4. Saari, J. M., and Shorthill, R. W.: Review of Lunar Infrared Observations. Boeing Scientific Research Laboratories Document D1-82-0586, Boeing Scientific Research Laboratory, Seattle, Washington, December 1966.

5. Weil, N. A.: Lunar and Planetary Surface Conditions, Advances in Space Science and Technology. Supplement 2, Academic Press, New York, 1965.

6. Shotts, Reynold Q., Cox, Robert M., Grubbs, David M., and Ahrenholz, H. W.: A Study of Lunar Resources: A Preliminary Report of Surface and Some Other Mining Systems. NASA Contract No. NAS8-20134, Bureau of Engineering Research, University of Alabama, University, Alabama, April 29, 1966.

7. Ronca, Luciano B.: An Introduction to the Geology of the Moon. Air Force Cambridge Research Laboratories, ARCRL-65-357, Special Report, No. 23, May 1965.

8. Surveyor I, Preliminary Results. Science, Vol. 152. June 24, 1966, pp. 1737-1750.

9. Wolkowitz, William, and Ramsh, Barry E.: Friction and Wear Between Unlubricated Metal and Nonmetal Surfaces. Grumman Aircraft Engineering Corporation Report No. RM-239, September 1964.

10. Determination of the Coefficient of Friction of Metals on Non-metals at Ultra-high Vacuum. NASA Contract NAS8-5415, Grumman Aircraft Engineering Corporation, May 15, 1964.

REFERENCES (Cont'd)

11. Penn, S. H.: A Preliminary Determination of the Coefficients of Friction Between Metals and Non-metallic Solids in Atmospheric and High Vacuum Environments. Note No. ADN 04-04-64-1, Grumman Aircraft Engineering Corporation, July 1964.

12. Gold, T.: The Lunar Surface. Monthly Notices Royal Astronomer Society, 115, 585, 1955.

13. Fudali, R. F.: Lunar Surface Characteristics. Bellcomm, Inc., June 25, 1963.

14. Ryan, J. A.: Ultra-high Vacuum Silicate Adhesion. J. of Geophys. Res., Douglas Missile and Space Systems Division, September 15, 1966.

15. Salisbury, J. W., Glaser, P. E., Stein, B. A., and Vonnegut, B.: Adhesive Behavior of Silicate Powders in Ultrahigh Vacuum. J. of Geophys. Res., Vol. 69, No. 2, January 15, 1964, pp. 235-242.

16. Halajian, J. D.: Soil Behavior in a Low and Ultrahigh Vacuum. Grumman Aircraft Engineering Corporation, 1964.

17. Fields, S. A.: The Behavior of Simulated Lunar Materials in an Ultrahigh Vacuum Environment. Presented at the 43rd Annual Meeting of the Alabama Academy of Science, Birmingham Southern College, Birmingham, Alabama, April 1-2, 1966.

18. Salisbury, J. W.: The Origin of Lunar Domes. Astrophys. J., 134, 1961, pp. 126-129.

19. Salisbury, J. W.: Natural Resources of the Moon. Nature, 195, 1962, pp. 423-427.

20. Westhusing, J. K. and Crowe, C.: Techniques for Lunar Water Exploration. Final Report, Contract No. AF 19(628)-3287, Air Force Cambridge Research Laboratories, September 30, 1965.

21. Design Data Handbook. Titanium Metals Corporation of America.

22. Dupont Titanium Information Bulletin No. 664-5. Harvey Aluminum Company, Titanium Seamless Pipe and Tube. Published by Joseph T. Ryerson & Sons, Inc., Boston, Massachusetts.

REFERENCES (Cont'd)

23. Mitchum, G. L.: The Application of Surface Mobility to Lunar Mining Operations, Third Annual Meeting, Working Group on Extraterrestrial Resources, John F. Kennedy Space Center, Cocoa Beach, Florida, November 18-20, 1964, pp. 151-159.

24. Paul, D., III: Economic Analysis of Extraterrestrial Propellant Manufacture in Support of Lunar Exploration. Proceedings, Fourth Annual Meeting Working Group for Extraterrestrial Resources, Air Force Academy, Colorado Springs, Colorado, Nov. 30 - Dec. 2, 1965, pp. 341-376.

25. Properties of T-6Al-4V, Titanium Engineering Bulletin 1. Titanium Metals Corporation of America, 1965.

26. Steels to Match Your Imagination. U. S. Steel Corporation, Design and Engineering Seminar, 1964.

27. Basic Design Facts About Titanium. Reactive Metals, Inc., Niles, Ohio. Form 1000-6606.

28. Green, J.: Some Lunar Resources. Proceedings, Lunar and Planetary Expl. Coll., N. American Aviation, Inc., Downey, Calif., III, No. 3, 1963, pp. 83-95.

29. Hayward, C. B.: A Preliminary System Concept for Extraterrestrial Mining and Processing Equipment. Third Annual Meeting, Working Group on Extraterrestrial Resources, John F. Kennedy Space Center, Cocoa Beach, Florida, Nov. 18-20, 1964, pp. 147-49.

30. Salisbury, J. W., Glaser, P. E., and Wechsler, A. E.: The Implications of Water as a Lunar Resource, Lunar and Planetary Colloquium, North American Aviation, Inc., Downey, California, III, No. 3, Nov. 1963, pp. 39-53.

31. Bensko, J. and Shotts, R. Q.: Lunar Resources. Progress in Space Science and Technology. Academic Press, New York, Vol. 7, 1965, pp. 147-214.

32. Williamson, T. N.: Hard Rock Tunnel Driving—On the Moon? Mining Engineering, 17, No. 7, 1965, pp. 147-151.

33. Delonis, S. L.: The Challenge of the 70's—Mining on the Moon, Mining Engineering, 18, No. 1, Jan. 1966, pp. 63-69.

34. Green, J.: A Study of the Feasibility of Using Nuclear Versus Solar Power in Water Extraction from Rocks. Final Report, Contract No. AF 19(628)-3292, Space and Information Systems Division, N. American Aviation, Inc., Downey, California, September 30, 1965.

35. Sauerman Tower Excavators Bulletin TX-2. Sauerman Bros., Inc., 1966.

36. Mining Engineering, No. 1, Jan. 1966, p. 76.

37. Kochanowsky, B. J.: Blasting Research Leads to New Theories and Reductions in Blasting Costs. Transactions AIME, 1955, pp. 861-866.

38. Kochanowsky, B. J.: Some Factors Influencing Blasting Efficiency, Mining Research, Pergamon Press, New York, 1961, pp. 157-164.

39. Langefors, U., and Kihlstrom, B.: The Modern Techniques of Rock Blasting. John Wiley & Sons, Inc., New York, 1963, pp. 18-42.

40. Rosenberg, S. D., Guter, G. A., and Rothenberg, G. A.: Requirements for On-site Manufacture of Propellant Oxygen from Lunar Raw Materials. Contrib. 263, Paper presented at Third Annual Meeting of Working Group on Extraterrestrial Resources, Cape Kennedy, Nov. 18-20, 1964.

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PROBLEMS AND TECHNIQUES OF LUNAR SURFACE MINING

By S. A. Fields and H. M. Weathers

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